Neutron source strength monitors for ITER

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There are several goals for the neutron source strength monitor system for the International Thermonuclear Experimental Reactor. Desired is a stable, reliable, time-dependent neutron detection system which exhibits a wide dynamic range and broad energy response to incident neutrons while being insensitive to gamma rays and having low noise characteristics in a harsh reactor environment. This system should be able to be absolutely calibrated *in situ* using various neutron sources. An array of proportional counters of varying sensitivities is proposed along with the most promising possible locations. One proposed location is in the preshields of the neutron camera collimators which would allow an integrated design of neutron systems with good detector access. As part of an ongoing conceptual design for this system, the detector-specific issues of dynamic range, performance monitoring, and sensitivity will be presented. The location options of the array will be discussed and most importantly, the calibration issues associated with a heavily shielded vessel will be presented.
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I. INTRODUCTION

The International Thermonuclear Experimental Reactor (ITER) is intended to be a long-pulse burning plasma experiment capable of providing the physics and technology database necessary to implement a demonstration fusion reactor. Determination of the time dependence of the neutron source strength (and hence the fusion power) is a fundamentally important measurement to the mission of the machine. Time-dependent monitors of neutron flux can provide a relative measure of the fusion power. If absolutely calibrated, the measured flux can be related to the total source strength of the fusion device.

The questions of whether and how to absolutely calibrate the source strength monitors drives the design of the system and the detectors. Given an absolute standard of neutron emission or fusion power, the time-dependent signal from any neutron-sensitive detector may be cross-calibrated to that standard and then used in a relative sense. Even if the source strength monitor system has its own traceable absolute calibration, the fusion power numbers should rely on an uncertainty-weighted average of all the determinations from different systems.[1] While activation systems and neutron camera systems may provide other absolute calibrations of fusion power, perhaps even more accurate ones, each additional absolutely calibrated system will reduce the uncertainties. It is not obvious that the radial neutron profile monitor will be able to achieve an accurate absolute neutron emission rather than just the relative profile. The neutron activation cannot have a ‘‘re-entrant’’ geometry as was successful on TFTR[2] and JET, and it is expected to end up with extremely radioactive samples which may be problematic in their analysis.[3] Each calibration technique has different uncertainties and is susceptible to different errors. Every effort to create an absolutely calibrated neutron system increases the probability of meeting the required 10% accuracy goals of the fusion power measurement for the ITER project. For reactor studies, the determination of the tritium breeding ratio requires even greater accuracy. It is thus imperative that an absolute calibration of the neutron source strength monitors is performed, as has been done for most previous working tokamaks since the 1970s. However, even if absolute calibration of the source strength monitors may be hard or inaccurate, we should strive for a relatively stable system that can provide routine and precise real-time information.

What are the desired requirements for the ITER neutron source strength monitor system?

- (i) Real-time source strength vs time with ~1 ms resolution
- (ii) reliable robust operation in an hostile environment
- (iii) wide dynamic range (seven orders of magnitude) from several detectors with redundancy to protect against single point failures
- (iv) large dynamic range possible in a single instrument through different electronic circuits
- (v) sensitive to neutrons, not gammas
- (vi) broad energy response, insensitive to changes in the neutron spectrum from ohmic to neutral-beam heated discharges
- (vii) relative insensitivity to positional changes of the neutron emission region
- (viii) low noise for calibration purposes
- (ix) stability of efficiency
- (x) electronics easily accessible for maintenance and repair
- (xi) ability to monitor discrimination settings
- (xii) need periodic ‘‘renormalization’’ from standard radioactive source (which must be removable to prevent burn-up by the radiation field)
- (xiii) the detectors themselves should be replaceable by remote handling if necessary.

We assert that the absolute calibration of an array of proportional counters on ITER is both desirable and possible and can meet these requirements. We would propose an array of 12 detectors: two detectors each at six different sensitivities, with no detector from the same sensitivity pair at the same location (for redundancy and avoidance of single point failure). These would be moderated and shielded ^{235}U fission proportional detectors with broad energy response. The sensitivity range would be achieved partially by changes in fissionable mass (up to a factor of 10^3 between 1 g and 10^{-3} g), partially by increasing the local shielding and moderation of the detectors (about a factor of 10), and by increasing distance (and hence shielding) of the detectors from the plasma (another factor of 10^3). The detectors would be operated in count rate mode to achieve good linearity for calibration purposes and to obtain gamma-ray rejection by pulse-height discrimination, and also operated in current mode to achieve the desired >1 kHz bandwidth.

II. REQUIRED DYNAMIC RANGE AND NUMBER OF DETECTORS

The expected peak fusion power for ITER is 1.5 GW or 5×10^{20} n/s. For a least-sensitive detector operating at <500 kHz count rate, this translates to an efficiency of $>10^{-15}$ counts/source neutron. This limit on count rate keeps dead-time corrections to the counting mode low; faster electronics on state-of-the-art detectors might increase this limit somewhat but not by more than a factor of 2 or 3. For calibration purposes, DT neutron generators are commercially available with 10^{10} n/s emission. A reasonable count rate during a calibration is 1 cps. Much less than that can suffer noise problems. At much higher count rates, statistically significant calibration results can be achieved in count durations far shorter than the typical time needed to move the point source and thus the calibration process is not significantly speeded up. Thus a system with 10^{-10} point efficiency (and about 10^{-9} total efficiency) is required to be the most sensitive system. Calibration to a ^{252}Cf radioactive source with 10^8 n/s emission would require a system with 10^{-7} total efficiency, which is difficult to achieve on a large system like ITER. For measurements from neutron generators to full ignited power operation, over six orders of magnitude dynamic range are required to be covered in sensitivity; we plan to design for seven orders.

The most sensitive detector only needs a few cps response to a calibration source, but it also needs to have linear response for plasma conditions used to cross-calibrate less sensitive detectors. A detector with 10^{-9} total efficiency running at <500 kHz count rate (to insure linear response) requires a plasma with $<5\times10^{14}$ n/s source strength for cross-calibration purposes. Ohmic plasmas at low current and density with high $Z_{\rm eff}$, even with considerable tritium recycling off the wall, should provide this level of neutron emission.

A sensitive detector, suitable for absolute calibration, will not quickly burn up in full-power ITER shots. One gram of uranium has 2.5×10^{21} atoms, and each atom requires a thermal neutron fluence of 1 n/cm^2 to fission. In a first wall fluence of a few 10^{13} n/cm^2/s, it would require about 10^6 s of high-power operation to burn up 1% of the detector, or 1000

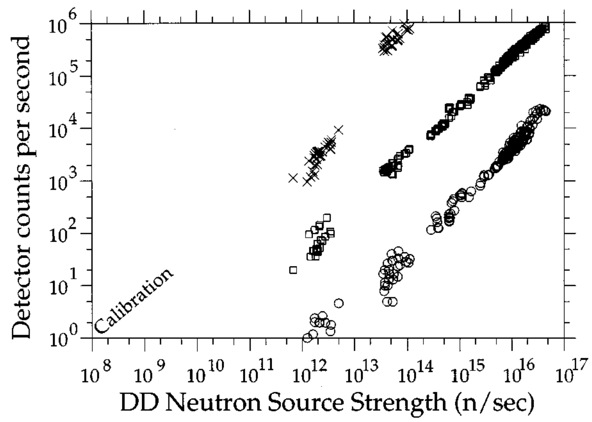

FIG. 1. Example of cross-calibration ladder (from TFTR) illustrating need for sensitivity overlap. The nonlinearity and variation around 10^{12} n/s source strength arises from large uncertainty in the Campbell mode signal used as the abscissa.

thousand-second discharges at full power. At that time one can place a source beside the detector and renormalize the efficiency. Any change in efficiency due to burn-up is easily computed. If the detector is behind any significant amount of shielding, the flux will drop dramatically and the time for burn-up to have an effect will increase beyond the lifetime of the experiment. Detectors with less fissionable mass would see burn-up effects sooner, but will be located at correspondingly further locations.

The total number of detectors then depends on the difference in sensitivity allowed. Figure 1 shows the count rates for three different detectors vs source strength on TFTR for a dataset circa 1987–1988 (a period of non-DT operation when three such detectors existed on the tokamak). This practically illustrates how cross-calibrations of less sensitive detectors proceeds. What is required for accurate cross-calibration is that both detectors (the more sensitive calibrated one and the less sensitive one to be cross-calibrated) are operated in linear modes with high precision. One thus desires both detectors to be in count mode (least questionable for its linearity), but at high enough count rates to reduce Poisson statistical uncertainties to $\leqslant1\%$ while not too high to create uncertainty in dead-time corrections. A difference in sensitivity of about 25 works best allowing count rates of between $\sim2\times10^4$ and 5×10^5 counts/s. Thus the total number of detectors needed is $n+1$ where $25^n=10^7$ or $n+1=6$. Failure of one detector would cause a gap of over 600 ($\approx25^2$) in sensitivity; thus two detectors of each sensitivity (approximately, but not necessarily exactly, the same) should be installed on the tokamak.

Different electronic modes (count, Campbell, current) can be used for the same detector to cover a wide range. Essentially three different sensitivity ranges of detectors on TFTR cover an equivalent dynamic range of seven orders of magnitude from 10^{12} n/s to almost 10^{19} n/s. But there are questions about the linearity of the detector electronics in current and especially Campbell mode, and the broad gap of count rate sensitivities on TFTR has caused problems in the cross-calibrations. Only count mode appears sufficiently re-

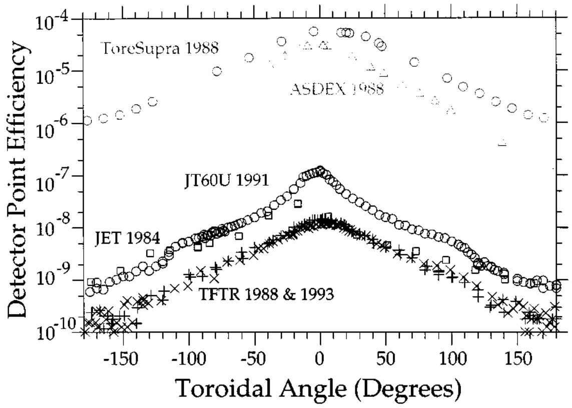

FIG. 2. Point efficiency vs toroidal angle relative to detector for ^{252}Cf neutron calibrations on several different tokamaks: Tore-Supra (circles at top), ASDEX (triangles), JT60U (circles), JET (squares) and TFTR (plus and x).

liable and linear to meet the accuracy requirements, and we think a set of 12 detectors should be designed and installed for ITER to extend this mode.

Operation in current mode can provide a precise, time-dependent signal with the required 1-ms time resolution. In count mode at 100 kHz, there are only 100 counts per millisecond and hence 3% Poisson statistical noise from time-point to time-point. While this is less than the desired 10% accuracy requirement, we desire a much more precise, low-noise, time-dependent signal such as current mode can provide. Current mode in fission chambers is not inherently gamma-insensitive. The detectors should have neutron moderators and lead shielding around them, and be compared to count mode where pulse-height discrimination makes the fission chambers gamma insensitive.

III. CALIBRATION

Can you get a detector close enough to achieve the desired 10^{-9} efficiency? There exists the belief that shielding of ITER will make this problematical. Placement of detectors in neutron camera preshields can help this. At such a location, if the detector was sensitive to 1/50–1/100 of the neutrons emitted towards it this efficiency would be achievable. Such low shielding is reasonable, but further neutronics design is needed.

Are such detectors sensitive to the plasma distribution of neutron emission? In 1988 a calibration of the TFTR was performed with over 1000 data points taken,[4] and we found only modest effects on toroidally integrated detector efficiency from spatial variations in the neutron source. This is likely to be the case for ITER, but the elongation and heavy shielding may enhance the effects due to spatial variation. The point efficiency for detection from the entire neutron emitting volume could be mapped out, obviating any need for neutron transport calculations to correct for plasma size or volume effects. The approximation of the neutron emission as a toroidal line source is very good. The expected sensitivity to changes in the position of the neutron emitting region is expected to be quite small for heavily shielded and moderated detectors.

Figure 2 shows the typical toroidal variation of the point efficiency from neutron calibrations on several different tokamaks. Calibrations for JT60U,[5] JET,[6] and TFTR[4,7] are all quite similar; the results from ASDEX[8] and Tore-Supra[9] show similar features but at the much higher efficiencies of the proportional counters used. The trend of all such careful calibrations is to minimize expectations of effects from unshielded views or odd geometries. This figure also illustrates the need for 10^{-10} point efficiency to angles away from the detector to get the desired 1 cps there, thus leading to a requirement for 10^{-9} total efficiency. While ITER is a larger tokamak than the present generation of large devices, this efficiency would still seem possible.

The operational plausibility of *in situ* calibrations on ITER is a concern. Since the fundamental mission of ITER requires accurate knowledge of the fusion power, we are certain that well-planned calibration activities leading to reduced uncertainties will be scheduled. Any *in situ* calibration on ITER, even before plasma operation, will face significant hazards if attempted to be done by hand. Thus all such calibrations should be designed to be performed by remote handling (moving the DT neutron generator remotely), and thus such calibrations should be possible during maintenance periods even if the machine is activated.

The ITER project would desire development of long-lifetime DT neutron generators with small anisotropy of emission and well-characterized output. However, isotropy of the source is not *necessary*, as the source can be oriented different ways and results added up to get a good answer.[4] Present commercial generators are large, clumsy, not particularly robust, and perhaps expensive for routine calibration purposes by remote handling equipment. Neutron generation using spherical electrostatic ion focus devices could provide an ideal calibration source, but presently achieved neutron emissions of 10^6 n/s in DD[10] need to be increased by factors of over 10–100 and demonstrated in DT to be useful.

Many of the examples and much of the experience in tokamak neutron calibrations come from ^{252}Cf or other radioactive source calibrations. Experience on TFTR leads us to believe that, except for the issues of emission anisotropy which have been easily dealt with and the generator technology itself, the techniques and procedures already developed in such calibrations will work well with the necessary DT neutron generators on ITER.

IV. FISSION CHAMBER DESIGN

Fission chambers are chosen because they are robust detectors with a proven performance in hostile environments such as fission reactors. They are also long-lived, gamma-insensitive, generally stable, very simple to operate, and provide real-time monitoring with time resolutions of much less than the 1-ms ITER specification. We would propose using moderated U235 detectors only (see Fig. 3). Less sensitive U238 detectors provided a measure of the DD/DT ratio on TFTR (for trace tritium or triton burn-up), but their absolute calibration was problematical. The very energy sensitivity that allowed a measure of the DD/DT ratio (better done by other techniques on ITER) also makes their response to beam-driven neutron emission a question. Moderated U235 fission chambers feature flat energy response across a large

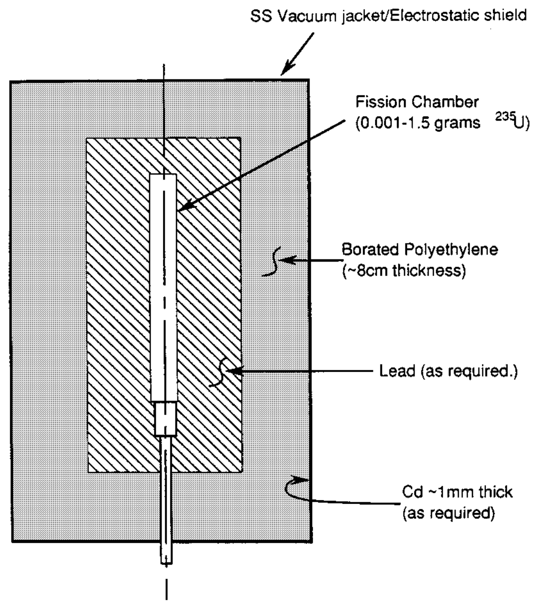

FIG. 3. Sketch of typical fission chamber "module" with typical components, shielding, and amount of moderator shown.

range of energies from 10 eV to 14 MeV. This is important to reduce sensitivity of the detector efficiency to changes in neutron energy spectrum. These detectors are gamma-insensitive and they can easily provide a real-time signal (especially in current mode) for machine operation. The dynamic range of a single detector could be a problem in a control system; one would need to put in signals from two or more into the control system. The detectors may have to operate in a vacuum jacket when located inside the cryostat. This jacket would also double as an electrostatic shield. The maximum operating temperature for such fission detectors is typically 300 °C, which should be compatible with cooled shield regions.

Commercially available detectors can have any incremental amount of U235 up to 1.5 g (up to 10 g for special requests) The minimum mass detectors are performance-limited to about 0.001 g. In all cases of operation in a high gamma flux, performance is greatly dependent on associated electronics. High count-rate electronics are required for optimum performance. Further dynamic range is gained by increasing the local shielding around the detector (for instance, adding a layer of boron) or by placing these gamma-insensitive detectors further away from the plasma, even out to the bioshield. At such distance, with machine shielding in front, a reduction in sensitivity of 10^3 may be expected.[11] Again, there should be at least two detectors at each specified counting range to handle failure of a detector without creating a gap in sensitivity.

Experience from TFTR, JT-60U,[5] and other tokamaks leads one to expect that as many as 10% of the installed detectors may soon have noise or discriminator drift problems. Thus we recognize the need for good access to the electronics (amplifiers and discriminators) of the proportional counters on a weekly maintenance period. However, shielding of the preamp/electronics is an issue, as the preamps work better the closer they are to the detector. The detectors themselves should have their sensitivity routinely checked by "renormalization," using standard radioactive sources placed next to them.[4] Finally, the detectors themselves may fail over periods of years, and plans are needed to replace the detectors by remote maintenance.

Note added in proof: A similar conceptual design for "neutron yield monitors"[12] reached similar conclusions.

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